N66 37969

THE UPPER ATMOSPHERE*

JAMES C. G. WALKER

The past four years of rocket and satellite measurements have significantly increased our knowledge of the upper atmosphere. For example, the variation of upper atmosphere density, which can be deduced from the rate of decay of satellite orbits, has been mapped out in considerable detail. It is plain now that the presently available reference atmospheres are seriously inadequate in their description of the atmosphere above 60 miles, especially in describing the variation of atmospheric properties with time. In fact, the international Committee on Space Research (Cospar) is working on a revision of its 1961 reference atmosphere that will reflect this recent information.

So fast is our knowledge of the upper atmosphere changing, however, that the new Cospar model could already be out of date, in some respects, by the time it is published. All of which merely underlines a fact that is often overlooked: while a standard model of the upper atmosphere may provide useful guidance in the design of vehicles and experiments to work in that environment, it is not likely that the model at any time will represent the upper atmosphere as we think it is, let alone represent it as it really is. We do not yet know the upper atmosphere as it really is, although we are much closer than we were four years ago.

FROM 60 TO 40,000 MILES

In looking at the upper atmosphere we are, by definition, concerned with what lies between the lower atmosphere (troposphere, stratosphere, and mesosphere) and outer space. This vast region, which includes virtually all of the ionosphere, extends upward from the top of the mesosphere, at an altitude of about 60 miles, to the magnetopause at 40,000 miles. (The magnetopause separates the region of space dominated by the earth's magnetic field from the interplanetary region dominated by fields and particles of solar origin.)

However, because atmospheric pressure and density decrease exponentially with increasing altitude, our knowledge of atmospheric properties is almost entirely limited to altitudes below about 600 miles. At higher altitudes, the densities are so low that, with few exceptions, our present-day experimental techniques are not able to detect the presence of the atmosphere at all, and we must base our models of this region on theoretical extrapolations from measurements made at lower altitudes.

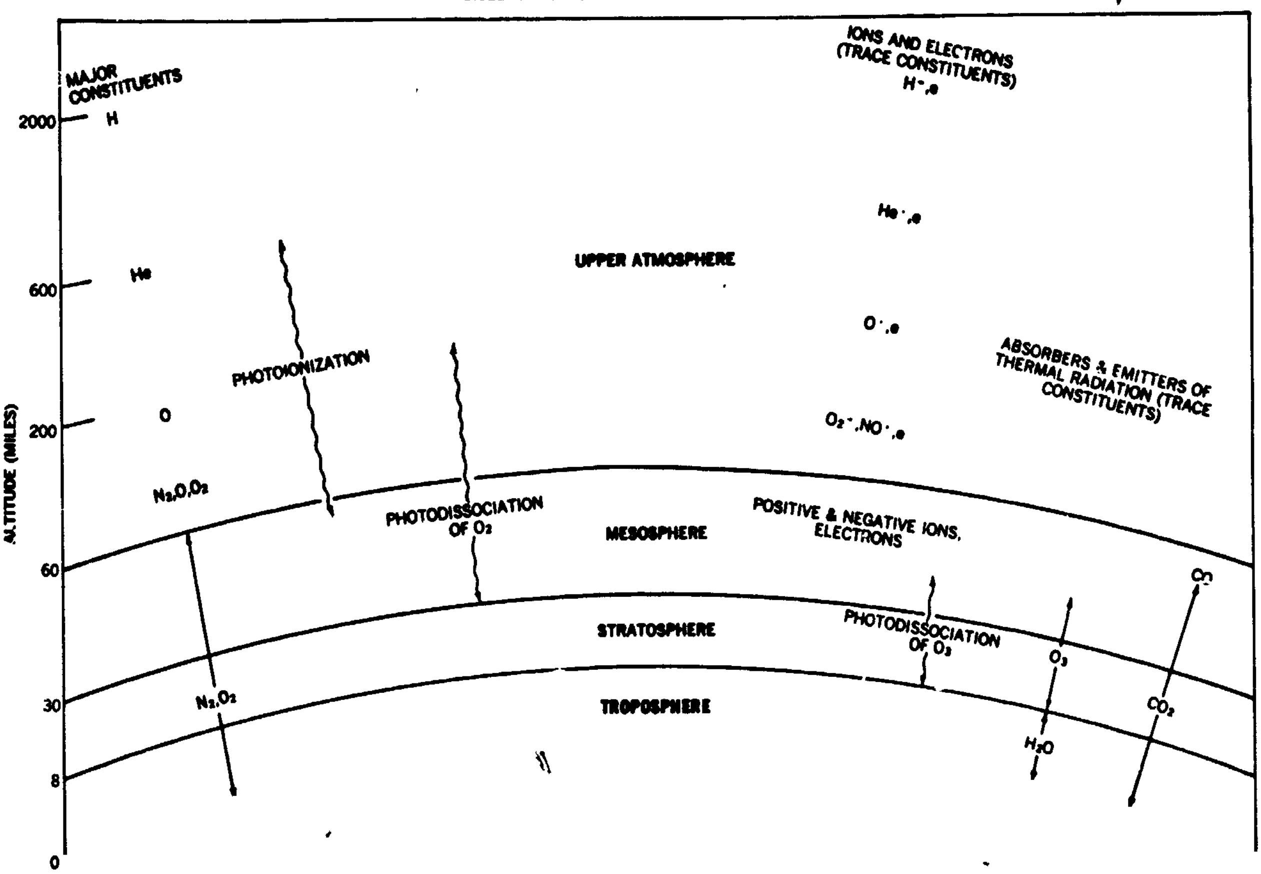
Thus, most of our discussion of the upper atmosphere of necessity refers to the region between 60 and 600 miles. Even within this range of altitudes the data coverage is not uniform. Very few satellites penetrate to altitudes below 120 miles, because at lower altitudes the atmospheric density and the resulting drag on the satellite are so high that the satellite can remain in orbit only a short while before falling back into the lower atmosphere. Accordingly, we must rely on sounding rockets to provide data on atmospheric properties between 60 and 120 miles, and the coverage in time and space which sounding rockets can provide is limited by the expense of rockets powerful enough to reach up into the upper atmosphere.

ONLY SMALL SAMPLES TO WORK WITH

In summary then, the data on upper atmosphere properties tend to be limited to isolated vertical profiles measured with sounding rockets and extending up to about 150 miles, and a considerable number of horizontal profiles measured with satellites and concentrated largely in the region from 180 to 400 miles.

Both the major atmospheric constituents and the trace constituents change with increasing altitude. How they change, why they change, and how their changes can be related to changes in temperature, pressure, and density, is what

*Published in *Space Aeronautics*, 42(4):56–63, October 1964.



SKETCH 1.—Upper atmosphere extends from mesopause out to magnetopause, as shown to scale in left section. A ten times expansion of scale in the right section shows how small is the layer below the mesopause that we call lower atmosphere.

recent rocket and satellite measurements have helped us to determine.

At the higher altitudes, light atoms (oxygen, hydrogen, and helium) are the major consituents. These constituents are atomic, rather than molecular, because their concentrations are so small at great altitudes that atoms seldom collide to form a molecule. The predominance of helium above about 600 miles is one of the new facts uncovered by recent satellite measurements; before this discovery there was thought to be a gradual transition from atomic oxygen to atomic hydrogen with increasing altitude. The important trace elements of the upper atmosphere are ions and electrons, resulting from ionization of the major constituents by solar ultraviolet radiation.

The altitude at which the upper atmosphere begins is defined by a temperature minimum. The temperature of the atmosphere reaches a maximum at 30 miles, the base of the mesosphere, then drops off sharply to the 60 mile base of the upper atmosphere. In the upper atmosphere, temperature rises steadily to around 1200 K (some 900 K above the mesospheric maximum). Because we have not yet found a way to measure upper atmosphere temperatures effectively, the temperature profiles have generally been deduced from measured composition and density profiles.

ENERGY PROCESSES KEY TO UNDERSTANDING

To understand the upper atmosphere—the complex behavior of temperature and composition as a function of altitude—we must consider its energetics. The energy transport processes, and the sources and sinks of energy, are what control the structure of the atmosphere. For the balance between energy gain and loss at any altitude determines the corresponding gas temperature. This temperature in turn controls the rate of change of pressure and density, through the law of hydrostatic pressure balance. At the same time, energy transfer leads to chemical changes in the atmospheric constituents and thus a variation of chemical composition with altitude.

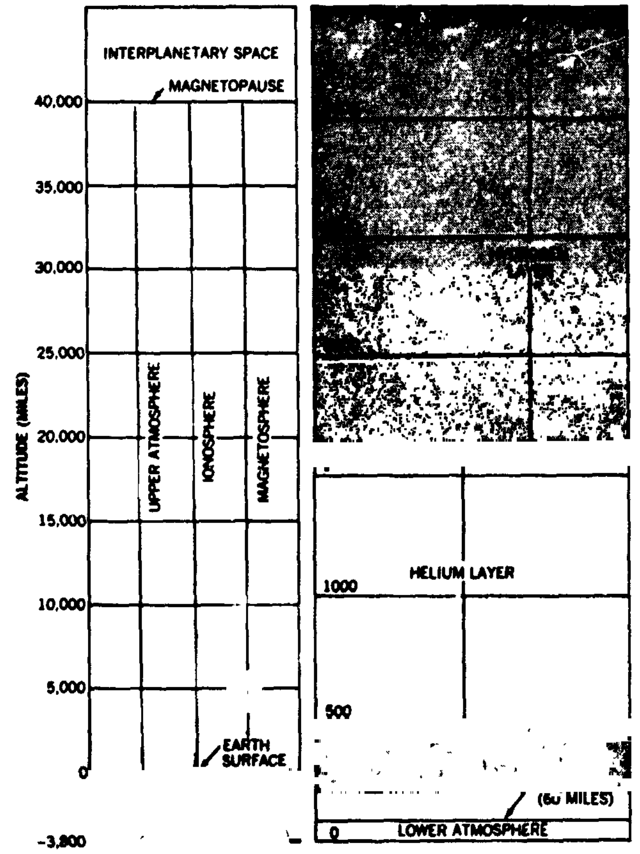
For all practical purposes, we can consider the sun to be the source of all the energy which influences the structure of our atmosphere. The flux of solar energy reaching the earth's surface is about a million times greater than the flux of energy conducted to the surface from radioactive heat sources in the deep interior. The energy fluxes carried by bombarding meteors and high energy galactic cosmic rays are also negligible.

SOLAR WIND MAY PLAY BIG ROLE

The atmosphere receives solar energy both from the sun's electromagnetic radiation and from the streams of protons and electrons flowing radially outward from the sun. Although the solar wind, as the latter streams are called, carries only one ten-millionth as much energy as the solar electromagnetic radiation, yet it may have an important influence on atmospheric properties at very high altitudes—particularly above 120 miles. This is an important question mark, as we shall see later when we consider how temperature varies with time.

Solar electromagnetic radiation varies in wavelength from infrared through visible, and into the ultraviolet. Although the energy carried by the solar ultraviolet radiation is only a small fraction of that carried by the visible in infrared, this energy is absorbed at fairly high altitudes where the atmospheric density is low and the energy transport processes are relatively inefficient. So there is a substantial temperature increase produced by the absorption of ultraviolet radiation.

There are two basic processes by which ultraviolet radiation is absorbed in the atmosphere. The most energetic photons, with wavelengths less than 1000 Angstroms, are able to knock an electron out of an atom or molecule when they are absorbed. The resulting formation of electrically charged particles, or ions, is known as photoionization. Photons with wavelengths greater than 1000 A do not have enough energy to ionize any of the atmosphere's major constituents. But they do have enough energy to break the weaker molecular bonds, specifically those which unite oxygen atoms into oxygen (O_2) or ozone (O_3) molecules.



SKETCH 2.—Scale on detailed cross section has been distorted for illustration purposes. Ultraviolet radiation from the gun is the principal source of energy in upper atmosphere: it reacts with major constituents by photoionization to produce ions and electrons, shown as Trace constituents at right above. Photoionization processes use up most of the sun's shorter wavelength ultraviolet radiation in the upper atmosphere. What remains to reach the lower atmosphere is less energetic and acts to dissociate molecular oxygen into atomic oxygen—around the mesopause, at 60 miles altitude—and to dissociate ozone at the base of the mesosphere. Very little ultraviolet radiation penetrates below the stratosphere. The solar radiation which penetrates into the lower atmosphere is in the visible and near-infrared portion of the spectrum. Neither of these are absorbed to any extent by the constituents of the atmosphere. The energy for the lower atmosphere comes from infrared radiation that is absorbed by the earth and reradiated in the far-infrared portion of the spectrum with maximum intensity at about 150,000 Angstroms. This radiation is strongly absorbed by water vapor and carbon dioxide in the troposphere and stratosphere. The absorption process is the energy source for the general circulation and weather phenomena that characterize the lower atmosphere. Our most recent knowledge of the upper atmosphere extends up to about 600 miles, but is limited at the lower end of the scale to around 120 miles by the requirement that the satellite last some months at least. Rocket soundings are used between 60 and 120 miles.

The resulting breakdown of the molecule is called photodissociation.

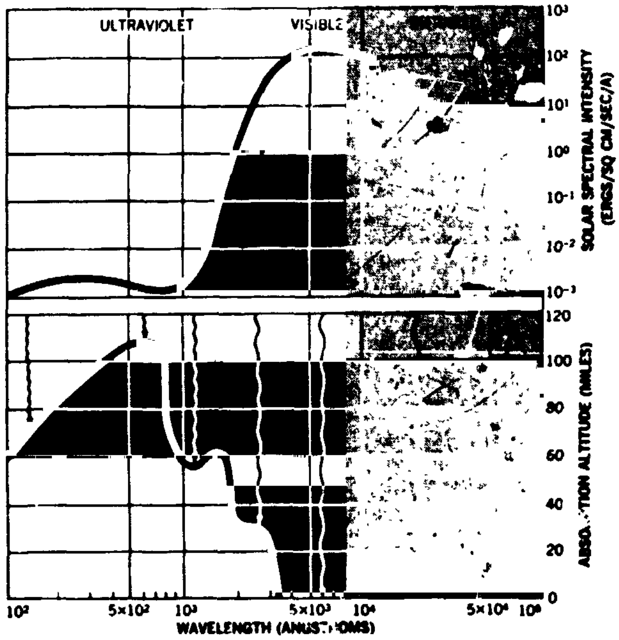
OZONE BREAKDOWN GIVES HEAT SOURCE

Photodissociation of oxygen is produced by the more energetic photons, with wavelengths between 1000 and 2000 A, and is most pronounced at about 60 miles altitude. The less energetic photons, with wavelengths of 2000–3000 A, penetrate even closer to the earth, into the stratosphere; there, they dissociate ozone, which is less tightly bound than oxygen. The temperature maximum at 30 miles attests to the importance of ozone photodissociation as a heat source. There is no corresponding maximum in the temperature profile around 60 miles where oxygen is photodissociated. But while oxygen absorption is not particularly important as a heat source, it does have a profound effect on the chemical composition of both the upper and lower atmosphere.

One result of photodissociation of oxygen is that much of the atmospheric oxygen at high altitudes is in the atomic state. The actual concentration of atomic oxygen is determined by the balance between the rate at which it is produced by photodissociation and the rate at which it recombines to form molecular oxygen. Theoretical treatment has so far failed to provide quantitative information on the relative concentrations of atomic and molecular oxygen in the upper atmosphere. Experimental measurements of atmospheric composition are difficult at high altitudes and at present are of doubtful reliability. Consequently, there is still some uncertainty about the composition of the upper atmosphere.

Below 60 miles, in the lower atmosphere, the atomic oxygen produced by photodissociation combines with molecular oxygen to form ozone. Present only in trace amounts, ozone is only one hundred-thousandth (10^{-5}) of the ambient density—even at 15 miles, where ozone concentration is a maximum.

Although ozone is only a trace constituent it plays a very important role indeed. By absorbing strongly in the near ultraviolet (between 2000 and 3000 A) it is not only shields the troposphere and the ground from this biologically harmful solar radiation, but also provides the energy source responsible for the temperature maximum where the stratosphere and mesosphere meet at

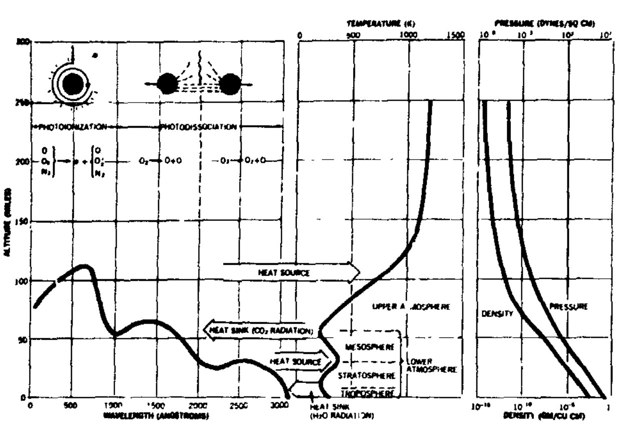


SKETCH 3.—Solar radiation controlling the structure of the atmosphere covers the range from extreme ultraviolet to infrared. Most of this radiant energy is in the visible and near-infrared, as the upper curve shows, and most of the energy in this region penetrates to the ground, rather than being absorbed by the atmosphere. Ultraviolet is absorbed at both high and medium altitudes. Comparison of upper and lower curves shows that greatest amount of absorbed ultraviolet is in the 2000–3000 A wavelength range; it is absorbed at altitudes of 25 to 30 miles.

the stratopause, 30 miles high. The rate of radiation absorption at any altitude is proportional to the product of the concentration of absorbing constituents and the radiation flux. Very little absorption occurs at high altitudes, where the concentrations are small. But by the time ultraviolet reaches low altitudes where concentrations are high, the radiation is attenuated. Here, the rate of absorption is low because the radiation flux is low. The maximum rate of absorption thus occurs at an intermediate altitude. The altitude at which the rate of absorption of any given wavelength reaches a maximum is called the absorption altitude for that wavelength.

ION-ELECTRON MAXIMUM 180 MILES UP

For extreme ultraviolet radiation of wavelengths shorter than 1000 A, the absorbing constituents are molecular nitrogen and oxygen, and atomic oxygen, and the absorption altitude is around 110 miles. The absorption occurs by way



SKETCH 4.—Variation of temperature with altitude is not undirectional as are pressure and density variations. Reversals in temperature curve are due to endothermic and exothermic reactions, the latter drawing on the energy created by the absorption of ultraviolet radiation. At the highest altitudes (100 miles or so) photoionization occurs when the most energetic ultraviolet photons (wavelengths below 1000 A) knock an electron out of the oxygen or nitrogen atom. The rapid temperature rise above 60 miles reflects this heat source. The temperature minimum at 60 miles is a consequence of the heat sink provided by the emission of thermal radiation by CO_2. The temperature rise of about 30 miles reflects the photodissociation of ozone.

of photoionization, producing free electrons along with the ions of the absorbing constituents. Because the rate of absorption is a function of altitude, it is to be expected that the concentration of ions and electrons will also be a function of altitude with a maximum at some altitude. This is, in fact, the case. Ions and electrons are present in detectable amounts at all altitudes above 40 miles, with the maximum electron and ion concentration occurring at about 180 miles. This layer of ionization is what is called the ionosphere. The region below the 180-mile ionization maximum is called the bottomside ionosphere; the region above is called the topside.

The greatest electron number density of the ionosphere is about 10^6 per cu cm, which amounts to only a thousandth of the neutral particle number density at the same altitude. Thus the ionosphere comprises only a small fraction of the total number of particles in the upper atmosphere.

Because it is central to an understanding of upper atmosphere energy sources, we would like to have a quantitative theory of the ionosphere which would allow us to calculate its properties and the way they vary in time without having to refer the measurements of these properties. We don't yet have such a theory. But, in the past three years, rocket measurements of the solar flux in the extreme ultraviolet region have made it possible, for the first time, to attempt to formulate one.

The theory is based on "airglow" measurements. Absorption of solar ultraviolet radiation by photoionization not only plays a central role in the formation of the ionosphere, but also leads to the excitation of atoms and molecules when ions and electrons from photoionization recombine. These excited species can radiate in their characteristic spectral lines and bands, which lie mostly in the visible region. This is called the airglow.

Because the airglow is excited predominantly in the chemical reactions and particle collision processes which follow the absorption of solar ultraviolet energy, airglow measurements constitute a valuable source of information on these reactions and collision processes and their occurrence in the upper atmosphere. Ground-based measurements of the airglow are fairly straightforward at night, and the first measurements of this kind were made 80 years ago. In fact, such measurements provided the earliest information about conditions in the upper atmosphere. During the day, however, sunlight scattered in the troposphere is many times brighter than the airglow, and it has not been possible until very recently to obtain any daytime airglow data. In the last two years, sophisticated ground-based and rocket techniques have yielded the first daytime airglow measurements. From these measurements we are gaining new insight into the reactions and energy conversion processes which take place at great altitudes when the atmosphere is sunlit.

AIRGLOW IS ENERGY SINK

It has been assumed that the theory of the daytime airglow would involve a simple extension of the theory of the night airglow, but the data now available have made it plain that completely unexpected energy transformation phenomena occur during the day.

We are particulary interested in the airglow because it represents an energy sink for the upper atmosphere. Only a part of the absorbed solar ultraviolet energy is released to the atmosphere in the form of heat; the rest of the energy escapes down to the ground or out into space in the form of airglow radiation.

We have been discussing ultraviolet radiation as if it were the only source of energy in the upper atmosphere. That this may not be exactly correct will soon be evident as we discuss the energy transport mechanisms and the implications of recent atmospheric density measurements.

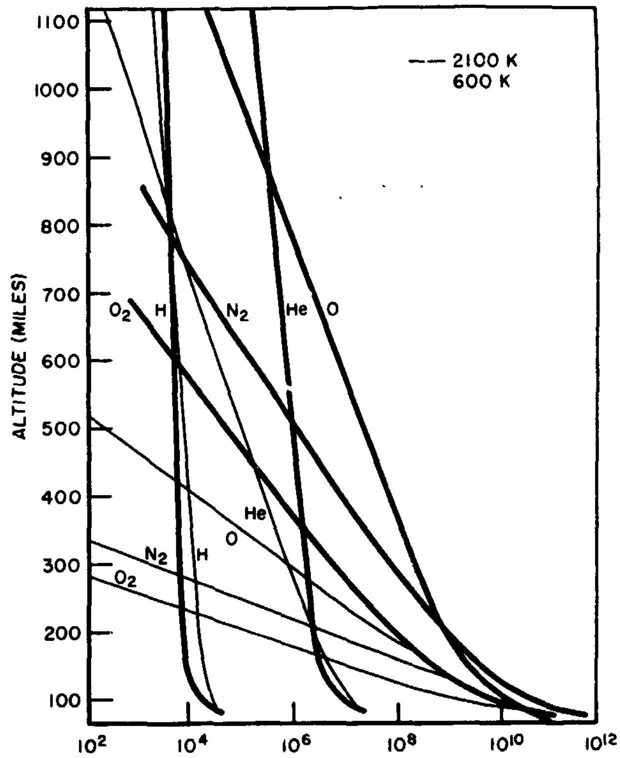
Cooling of the upper atmosphere by the emission of thermal radiation is negligible. The atmospheric molecules which have spectra in the infrared, and can therefore emit thermal radiation at atmospheric temperatures, are water and carbon dioxide. But these molecules are very rare in the upper atmosphere where they are subject to photodissociation by solar ultraviolet radiation.

NO MIXING MECHANISM AVAILABLE

Convection also turns out to be unimportant above 60 miles because temperature increases with altitude, making the atmosphere stable. This inhibition of convection has a profound effect on the composition at great heights. In the absence of convection, and the turbulence which results from convection, there is nothing to keep the atmosphere well-mixed and reasonably homogeneous. Instead, a regime of diffusive equilibrium is maintained. The heavier atmospheric constituents settle out at fairly low altitudes under the action of gravity, while the lighter atmospheric constituents, which are less tightly bound by the earth's gravitational field, rise above them and become increasingly important as altitude increases.

The number densities of these constituents, both light and heavy, decrease with altitude at a rate that depends on the temperature. However, these densities are so low that the temperature at these altitudes cannot be measured directly. Instead, the temperature must be deduced indirectly from measurements of other atmospheric properties. Above 120 miles, atmospheric densities can be deduced from the orbital decay of satellites as the result of atmospheric drag.

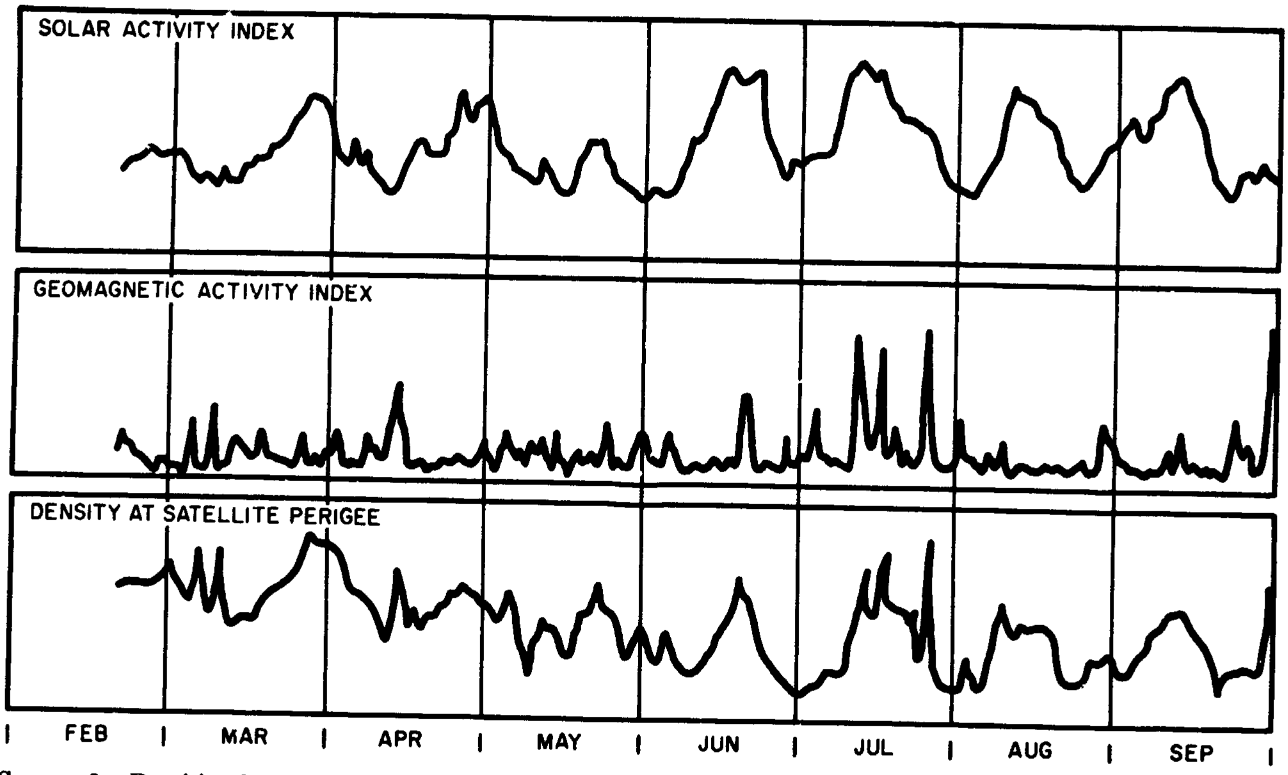
Drag studies have been our most prolific source of information on the upper atmosphere, and they have revealed enormous variations of density with time. Because the density at any altitude is sensitive to the temperature, the density variations are believed to reflect variations in tempera-



SKETCH 5.—Altitude variation of number density of major constituents in upper atmosphere, plotted for two different temperatures. These curves show how lightest constituents persist to highest altitudes and how rate of fall-off in density is a function of temperature. The relationships, determined theoretically using hydrostatic balance and the ideal gas law, have been confirmed qualitatively by satellite measurements. This confirmation supports the validity of our present indirect method of deducing upper atmosphere temperatures from density measurements.

ture that are caused by changing heat sources. Most of the variations can be explained, at least qualitatively, as the result of changes in the ultraviolet heat source caused by changes in the solar ultraviolet flux.

One phenomenon, however, cannot be explained on this basis and is therefore of particular interest. The satellite drag densities show sharp and sudden increases at times of geomagnetic storms, which show up as spikes in the geomagnetic activity index. Since magnetic storms (unusually large variations in earth's magnetic field, measured at its surface) occur about a day after intense solar flares, it has long been believed that these storms are caused by the impact on the earth's magnetic field of streams of charged particles emitted by the sun at the time of the flare. (These particles



SKETCH 6.—Densities deduced from drag measurements on 12-ft-diameter balloon satellite, Explorer 9 (bottom curve) during February through September 9, 1961, show close correlation with ground-based-measurements of solar, or sunspot, activity (top curve) and disturbance of the earth's magnetic field (center curve). Solar radio flux (10.7 cm), which is used as index of solar activity here, appears to be roughly proportional to flux of extreme ultraviolet radiation which is the heat source (by photoionization) for the upper atmosphere. Curve of temperature at satellite perigee would be essentially identical in shape with density curve.

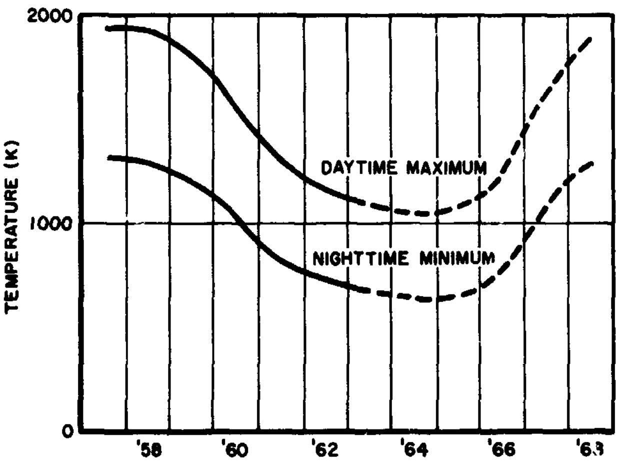
take just about a day to travel from the sun to the earth.) Because of the coincidence between the density spike and the spike in magnetic storm activity, it is presumed that the heat sources which are responsible for the sudden increase in upper atmosphere temperature and density derive their energy from these streams of charged solar particles.

ULTRAVIOLET NOT SOLE ENERGY SOURCE

The geomagnetic activity effect, as this phenomenon is called, provides the strongest evidence we have for an energy source in the upper atmosphere other than that provided by the absorption of solar ultraviolet radiation. Because magnetic storms are comparatively infrequent, this does not constitute evidence for more than an intermittent additional heat source, and it is not yet clear whether this additional heat source (called the corpuscular heat source because it derives its energy from the solar wind) is important in determining the average conditions in the upper atmosphere.

We have mentioned how the inadequacy of our knowledge of upper atmosphere composition may introduce errors in the temperatures deduced from satellite drag data. In an attempt to obtain direct measurements of upper atmosphere temperatures, attention was turned early in the space age to rocket and satellite experiments which could determine the temperature of the electrons in the ionosphere above 60 miles. Measuring the temperature of the electrons in the upper atmosphere is considerably easier than measuring the temperature of the neutral particles (which have no charge), and techniques borrowed from plasma physics have been applied with some considerable success.

It was not clear, when the first measurements were made, whether or not the electron temperature would be equal to the neutral gas temperature. Because the mass of the electron and the



SKETCH 7.—Temperature in isothermal region above 120 miles varies during the solar sunspot cycle. Solid line shows temperature deduced from densities measured by satellite drag. Broken line shows predicted values for remainder of solar cycle (after Harris and Priester). Maximum temperature of 2200K occurs in afternoon during solar cycle maximum. Minimum temperature of 600K at dawn occurs at solar cycle minimum (solar maximum and minimum occur about 11 years apart). Recent discovery of this time variation of temperature is one reason Cospar standard atmosphere model is now undergoing revision.

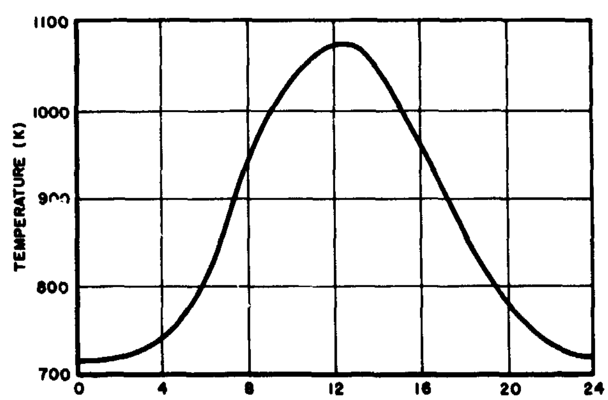
mass of the neutral particles are very different, the electron gas in the upper atmosphere is in poor thermal contact with the neutral particle gas. The early measurements indicated that the electron and neutral gas temperatures were equal above 250 miles but that during the day the electron temperature was considerably higher than the neutral gas temperature at lower altitudes. This finding was in accordance with theoretical studies which predicted that photoionization—concentrated at about 110 miles—heats the electron gas more than the neutral gas.

More recent electron temperature measurements, using the Ariel 1 and Explorer 17 satellites and the ground-based radar backscatter technique, have indicated that the early measurements were misinterpreted. The electron temperature is, in fact, greater than the neutral gas temperature at all altitudes and at all times of day.

This misinterpretation of the early measurements illustrates the danger of trusting the reference atmospheres. The early electron temperature measurements were made in 1960 and 1961 and the results were compared with the gas temperatures contained in the 1962 U.S. Standard Atmosphere—which more or less reflects conditions as they were in 1958. The comparison showed that electron and gas temperatures were approximately the same. However, by 1961 the neutral gas temperature had declined with the decrease in solar activity to values considerably below those given by the standard atmosphere.

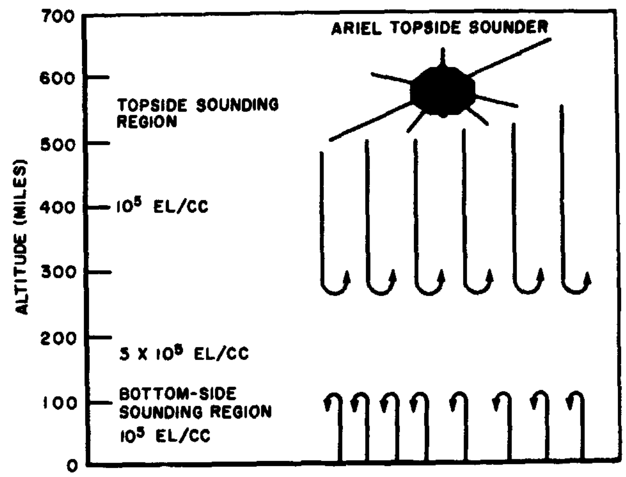
So if the early measurements are reinterpreted in the light of our more recent knowledge of neutral gas temperatures, they agree with the latest electron temperature measurements in indicating that electron temperatures are invariably higher than the neutral gas temperatures. It is therefore not possible to determine neutral gas temperatures in the upper atmosphere by measuring the electron temperatures. Just this year, however, it has been realized that the electron temperature data present a more exciting possibility. The electron temperature, it turns out, is so sensitive to variations in the upper atmosphere heat source that it is possible to deduce the absolute magnitude of the heat source from measurements of the electron temperature.

The first work along these lines has been carried out using the Ariel 1 data, and a similar analysis is now being applied to the Explorer 17 results. These analysis provide our first direct information on upper atmosphere heat sources. It is still too



SKETCH 8.—Daily variation of upper atmosphere temperature based on satellite drag measurements of density (after Harris and Priester) in 1962. A recent theoretical treatment of this variation showed it could not be explained on the basis of an ultraviolet heat source; an additional heat source, of approximately equal mangitude, had to be postulated. Presumably this may be a corpuscular source, derived from the solar wind. Very little is yet known about this corpuscular heat source and its importance is controversial. Electron temperature measurements made by Ariel 1 and Explorer XVII may help.

early to tell for sure, but it appears that the daytime heat sources deduced from these data are consistent with the heating that would be expected to result from the absorption of solar extreme ultraviolet radiation. There is no clear evidence in the daytime results of a non-ultraviolet or corpuscular heat source. On the other hand, the electron temperature measurements show clearly that there must be a nighttime source of energy which, while only one percent of the daytime heat source, is still enough to raise electron temperatures a few hundred degrees above the neutral gas temperatures. Since this heat source cannot be attributed to the action of solar ultraviolet radiation, it provides strong evidence for the existence of a non-ultraviolet heat source at night. This nighttime energy source may well be provided by a flux of low energy electrons bombarding the atmosphere from above.



SKETCH 9.—Electron density in ionopshere falls of above and below electron density maximum at 200 miles altitude. Numbers on chart indicate density in electrons per cu cm. Density measurements, made from the ground by radio wave reflections, have long been confined to bottom-side sounding region because no radio waves are reflected to earth from above the density maximum. With advent of satellites capable of making radio soundings from above, electron density measurements of the topside have become possible.

ONLY CONDUCTION IS IMPORTANT

Whether the upper atmosphere heat source is provided by ultraviolet radiation or bombarding electrons or both, the neutral gas temperature is ultimately determined by the rate at which heat transport processes can remove the heat which the sources release. Since both convection and radiation cooling are unimportant, thermal conduction is all that is left to remove heat from the upper atmosphere. In a gas, conduction is a notably inefficient process of heat transport. So it doesn't require a large heat source to maintain the very high temperatures which are found at great altitudes. In fact, the solar extreme ultraviolet radiation, which is believed to provide the major source of heat at high altitudes, carries an energy flux of only about 3 ergs/sq cm/sec. For comparison, the energy flux in the visible region of the solar spectrum—which is responsible for heating the ground and the lower atmosphere—is a million times as large.

The heat which is deposited by the solar ultraviolet radiation at about 110 miles is conducted from this high temperature region down to the very low temperature (200 K) mesopause. At the mesopause a heat sink is provided by infrared-radiating molecules of water and carbon dioxide—which are relatively abundant at low altitudes. The balance between the rate at which heat is conducted to the mesopause and the rate at which heat is put into the upper atmosphere is what determines the temperature of this higher region. The theoretical problem is in principle quite straightforward, although sophisticated computational techniques are made necessary by the fact that the heat sources vary with time and with the density and composition of the upper atmosphere, and the fact that these latter quantities in turn depend on the temperature.

A recent theoretical treatment of the diurnal variation of upper atmosphere temperature showed that the observed temperatures could not be explained on the basis of an ultraviolet heat source alone. It was necessary to postulate an additional heat source, presumably corpuscular, equal in magnitude to the ultraviolet. Although it is too early to say for sure, this conclusion may conflict with the deductions from electron temperature measurements. In any event, we need more positive evidence—not simply a disagreement between experimental and theoretical values of temperature—to prove the importance of the corpuscular heat source.

The problem with postulating a corpuscular source is that the charged particles of the solar wind cannot penetrate beyond the boundary of the earth's magnetic field at about 40,000 miles altitude and thus cannot interact directly with the upper atmosphere. Although the Mariner 2 measurements have told us what the energy flux in the solar wind is, there have been no similar measurements which could tell us how much of the solar wind energy is able to cross the boundary and travel down through the earth's magnetosphere, to show up as a heat source in the upper atmosphere at altitudes of 100–200 miles.

TURBULENT INTERACTION NOT YET PROVEN

It is presumed that there must be a turbulent interaction between the solar wind and the earth's magnetic field leading to the production of hydromagnetic waves, or fluxes of energetic charged particles, which travel down through the magnetosphere and deposit their energy in the upper atmosphere. But there are no quantitative theoretical treatments of any of these processes which would let us estimate the magnitude of the corpuscular heat source.

Several attempts have been made to locate flaws in the theoretical treatment of the heat conduction equation in the upper atmosphere in the hope that these flaws might account for the disagreement between the measured temperatures and the temperatures calculated with an ultraviolet heat source only. To date none of these attempts have been successful, and the discrepancy stands as one of the most interesting recent results in upper atmosphere physics. What it amounts to is this: we do not yet understand the physics of the upper atmosphere well enough to be able to calculate, from first principles, temperatures which agree with the measurements.

Calculation of the temperature is the fundamental goal of atmospheric structure theory because the temperature profile controls the pressure and density profiles through the requirement of hydrostatic balance. So a calculation of the temperature profile leads at once to the determination of overall atmospheric structure. In addition, because the energy sources responsible for temperature changes also lead to changes in chemical composition, an adequate understanding of the temperature and the energy sources which it reflects necessarily implies a thorough understanding of the chemical composition of the atmosphere. This goal is closely related to the immediate practical problem of predicting the conditions which are likely to be encountered by our space probes in the atmosphere of the other planets.

Selected Bibliography

Upper atmosphere physics has developed so rapidly that textbooks naturally lag behind current developments. One of the few books available is Space Physics, *edited by D. P. LeGalley and A. Rosen; Wiley, '64. / Another book available: J. A. Ratcliffe (ed.),* Physics of the Upper Atmosphere; *Academic Press, '60. / Professional journals are the most useful sources of current information. Jacchia has reviewed satellite drag measurements of upper atmosphere density in* Reviews of Modern Physics; *Vol. 35, pp. 973-991, '63. / The results of inospheric experiments using rockets and satellites have been described by Bourdeau in* Space Scienec Reviews; *Vol. 1, pp. 683-728, '63. / Readers seeking more details on current research will find the* Journal of Geophysical Research, Planetary & Space Science, *and* Space Research *journals most useful.*

N64-19010

INFERENCES OF STRATOSPHERIC AND MESOSPHERIC CIRCULATION SYSTEMS FROM ROCKET EXPERIMENTS*

G. WARNECKE† AND W. NORDBERG

Recently performed rocket grenade experiments at Wallops Island and Churchill and MRN data are interpreted to show the existence and movement of conventional circulation systems throughout the upper stratosphere and mesosphere. Evidence of moving pressure systems exists up to an altitude of 70 km where the nature of the circulation changes abruptly. Also, the pattern of the pressure systems in the stratosphere (below 50km) seems to be different from the pattern inferred at higher altitudes (50—70 km.)

INTRODUCTION

Since the early rocket grenade experiments more than ten years ago and the successful firings during the IGY period, the experiments have been continued by NASA at Wallops Island. Thus a large number of soundings is available giving already a climatological survey on the gross features of the winds and the thermal structure in the upper stratosphere and in the mesosphere (1) (2). Experiments have also been performed in Australia, Japan, Sweden, Italy, and France and the United States program will be extended to include simultaneous launchings at Churchill, Wallops Island, and Ascension Island. (3) The number of rocket stations reporting data above the normal Meteorological Rocket Network (MRN) levels is gradually increasing promising an improving global data coverage for the levels between 50 and 90 kilometers during the forthcoming International Geophysical Year (IQSY). In this report, interesting features are derived from the first simultaneous rocket grenade experiments performed at Churchill, Manitoba, and Wallops Island, Virginia, and from simultaneous Meteorological rockets launched at the various MRN sites over North America. While the earlier sporadic experiments enabled a study of climatological gross features of the mesospheric circulation, these simultaneous observations have encouraged us to investigate the dynamic structure of the mesosphere on a smaller scale by means of synoptic presentation of flow patterns for selected days over the North American continent. At the higher altitudes, the acoustic temperature and wind measurements were supplemented by other sounding techniques such as wind measurements by means of sodium vapor release.

THE VERTICAL CHANGE IN STRATOSPHERIC AND MESOSPHERIC WIND STRUCTURE

Considering the seasonal variations of stratospheric and mesospheric winds as measured at Wallops Island over a period of 3 years, one finds a remarkable change in the behavior of mesospheric winds around the height of 70 km. Below this level, the wind follows a consistent and predictable seasonal pattern while above 70 km the wind structure becomes very irregular and does not show the well-known regular features observed at levels up to 70 km (2).

This fact is apparent in figure 1, where all rocket grenade winds for the years 1960 through 1963 are presented in polar diagrams for the lower, middle, and upper mesosphere. The winds in the 45–55 km layer show the same general features as in the stratosphere: strong and relatively steady westerly winds with maximum deviations of $\pm 25°$ about an average direction of 265° and light but equally steady easterly winds in summer. During the transitions between winter and summer sea-

*Published as *Goddard Space Flight Center Document X–651–64–22*, January 1964; also published in Proceedings of 5th International Space Science Symposium, Florence, Italy, 1964, North Holland Publishing Company, Amsterdam.

†Goddard Space Flight Center; on leave from Institut für Meteorologie and Geophysik der Freien Universität Berlin, Berlin, Germany, as National Academy of Sciences-National Research Council Research Associate with National Aeronautics and Space Administration.

sons, there is a large variability in wind strength and direction; however, this variability is still part of a consistent seasonal pattern which has been the subject of several previous analyses (4). In the middle mesosphere (60–70 km) one finds qualitatively the same behavior, although varia-

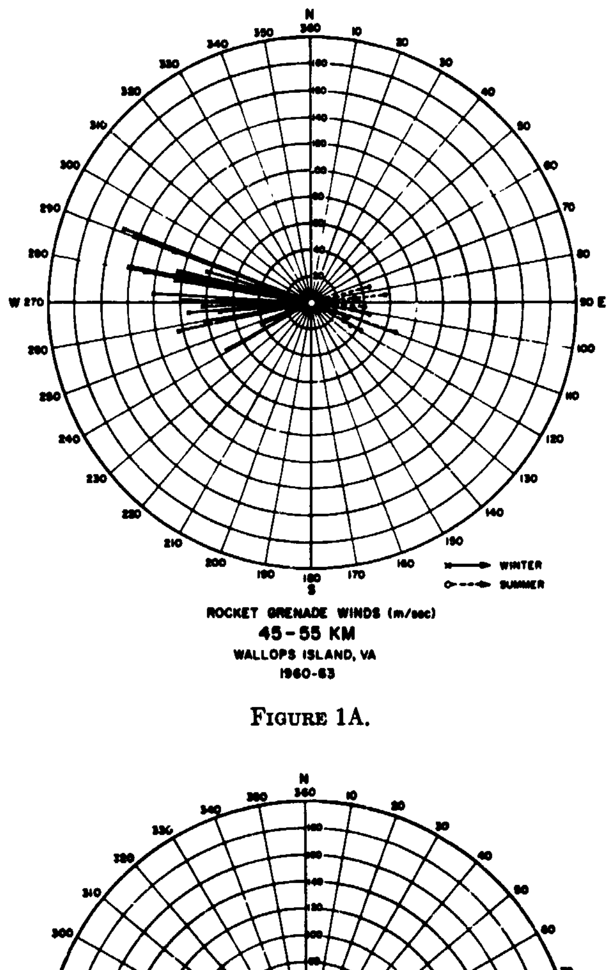


FIGURE 1A.

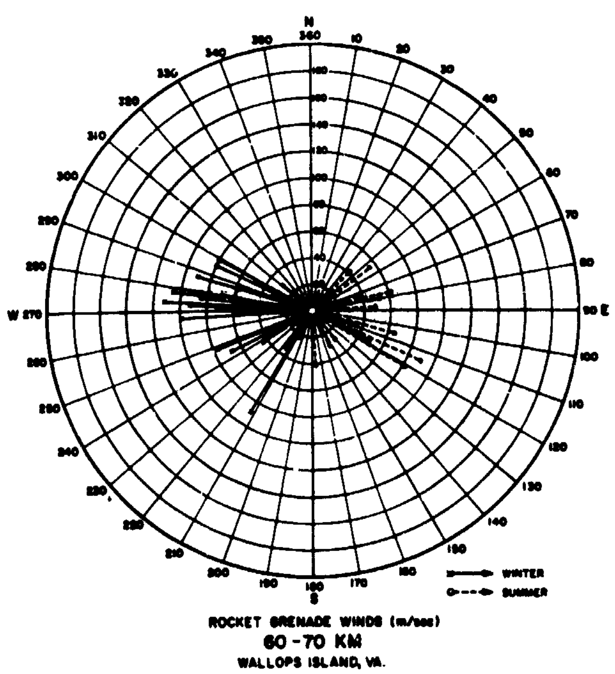


FIGURE 1B.

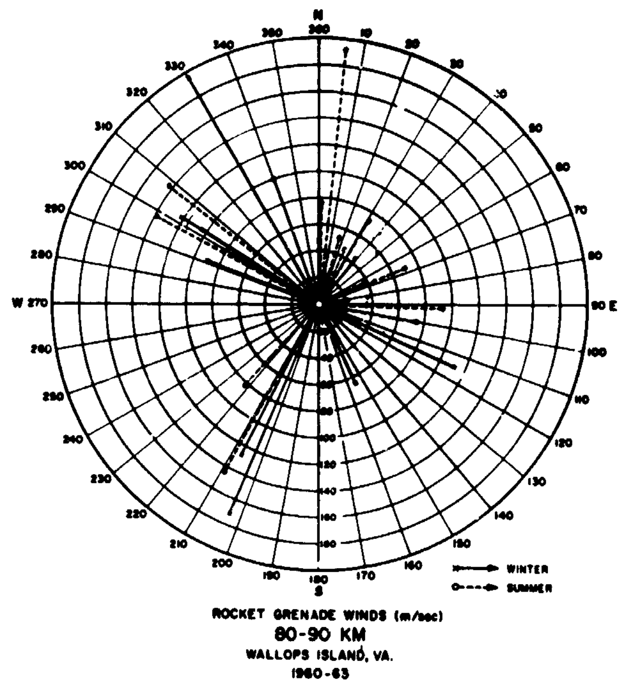


FIGURE 1C.

tions in the wind directions are somewhat larger. In the upper mesosphere (80–90 km), however, the picture changes completely. The winds both in winter and summer are blowing from all directions and in highly variable strengths. The same characteristics are shown by the results of recent sodium vapor release experiments at Wallops Island (5). In figure 2 wind direction profiles from five experiments reaching below 70 km are reproduced, and the drastic change in wind structure between 70 and 80 km is apparent.

From these rocket observations with both the grenade and sodium release methods, one may conclude that above a transition layer between 70 and 80 km the dynamic behavior of the mesosphere becomes so complex that synoptic representations of the flow patterns on a Time scale of days will be meaningless. On that scale, the motions above this layer appear to be highly "disorganized" and it seems that for synoptic presentations Time scales of the order of an hour or so will have to be employed at altitudes higher than 80 km. Therefore, such an abrupt change in the wind structure may very well be due to the increasing importance of tidal motions and possibly in the fact that the atmospheric structure as a whole undergoes basic and major changes at the 80 km level.

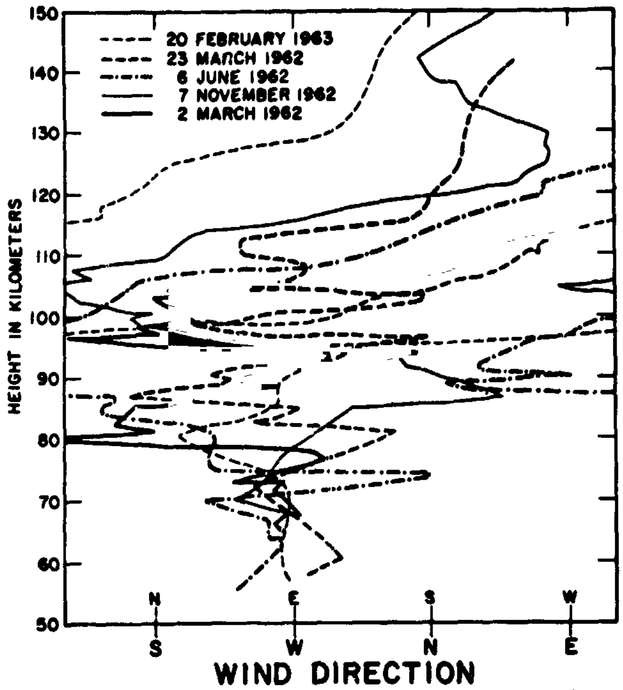


FIGURE 2.

Nevertheless, up to this level the mesospheric motions are still organized in the usual meteorological sense, and synoptic presentations are quite justified and well representative of the strea patterns over periods of several days.

INFERRED MESOSPHERIC SYNOPTIC CIRCULATION SYSTEMS UP TO 70 KILOMETERS

Several investigators have already extended presentation of synoptic weather maps up to the 0.5 or 0.4 mb level (about 55 km) by using Meteorological Rocket Network data (6), (7), (8), (9). In this paper, an attempt is made to construct synoptic maps up to the 0.05 mb level (68 km) for a few special days by making use of recent grenade and MRN data.

Data from the first simultaneous rocket grenade soundings at Churchill and Wallops Island, in early December, 1962, (10) were analyzed in addition to Meteorological Rocket Network data (11) also available for that time period. Variation of flow and pressure patterns for various upper stratospheric and mesospheric levels over the American continent were investigated by constructing synoptic maps for 4 December and 6 December, 1962. In these maps, the pressure fields at constant heights are presented. Using the geostrophic approximation, the isobars were spaced such that each pressure field is in accordance with the observed winds. The pressure values of the isobars were determined by the observed pressures over the discrete points of observation.

The circulation in the lower stratosphere (100 mb or 16 km) around 5 December, 1962, was characterized by the displacement of the cold polar vortex to Siberia, the entire North American continent being under a rather uniform westerly stratospheric flow with a slowly developing trough moving gradually eastward over the United States (figures 3) (12). The middle stratosphere (30 mb or 23 km) (figure 4) shows a quite different stream pattern over the entire western hemisphere (13) with a weak but, nevertheless, unusual quasi-stationary anticyclone over Canada and a zonally oriented trough over the United States along 40 deg. latitude. In the upper stratosphere (10 mb or 30 km) the same contour pattern appears with greater intensity: the easterly wind at the southern flank of the Canadian anticyclone exceeds 25 m/sec (50 knots), whereas a stratospheric jet stream with winds up to 50 m/sec (100 knots) is located over the Gulf coast (figure 5). There are no significant changes of the circulation pattern at 30 km within the period of December 4–6, 1962, so that figure 5 applies to this interval. The North American high pressure systems represent an eastwardly displaced Aleutian anticyclone that governed the Northern hemispheric circulation throughout November (14) and is still apparent at the 5 mb surface, which was constructed for 5 December, 1962, (figure 6). The 40 km pressure maps (figure 7) show the pronounced trough over the Great Lakes area moving slowly southward, whereas the existence of the Canadian anticyclone is not necessarily indicated at this level. Its center may well have shifted to the Pacific region, Alaska and Canada being in the regime of the polar vortex. The anticyclone can still be observed ten kilometers higher (figure 8), and here there is a definite indication that its center has shifted northward, causing a nearly northerly wind over Churchill on 4 December and a southwesterly wind over Alaska. Although the stream pattern remains essentially the same at

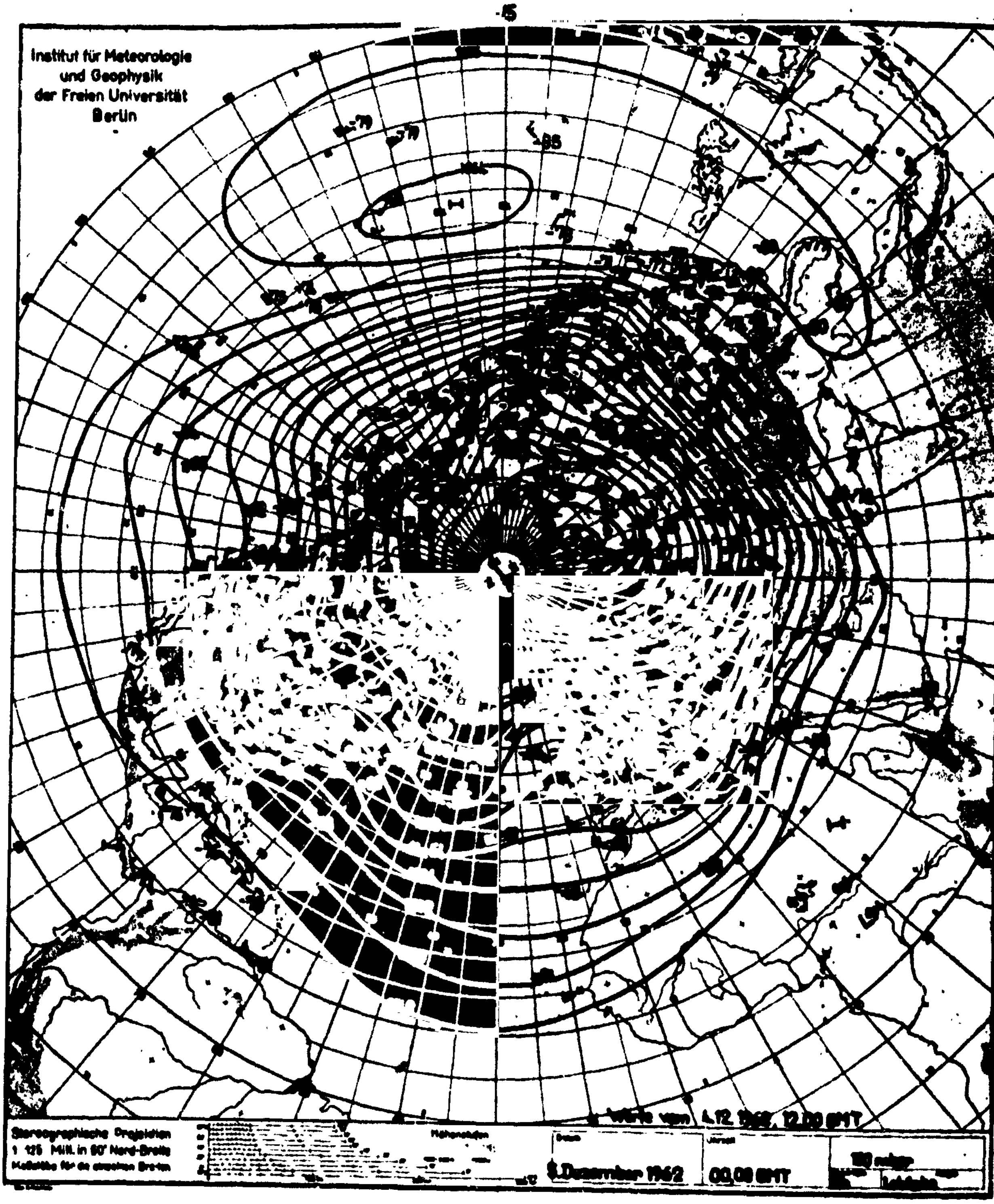


FIGURE 3

60 km (figure 9), there is a distinct further shift in the position of the center of the anticyclone. It is apparently displaced to the Arctic, as indicated by the southeasterly wind over Alaska. The pronounced trough, which has persisted at all altitude levels from 23 km up, is still located over southern Canada; and there is some indication that its vertical axis is slightly inclined to the

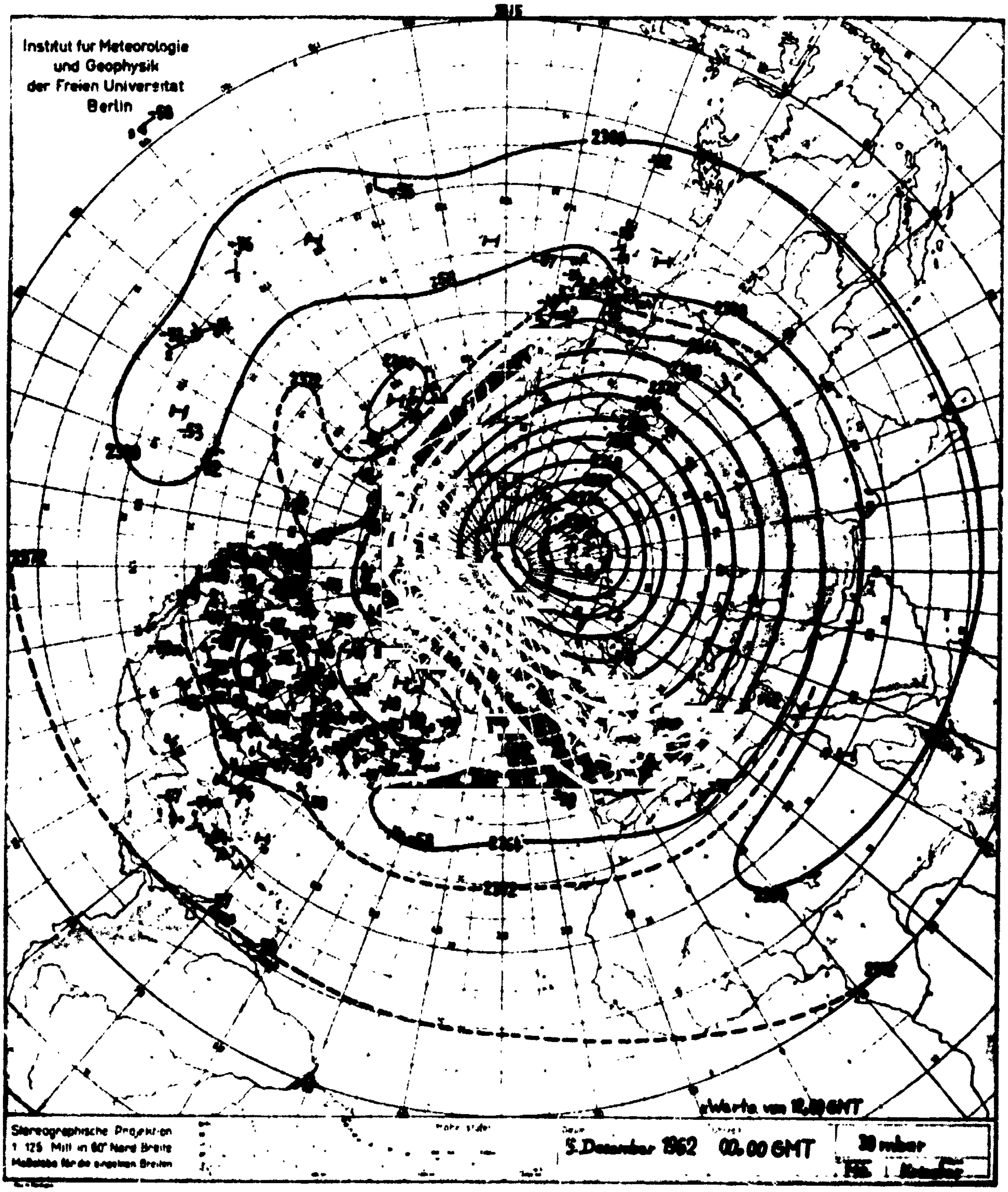


FIGURE 4

north, such that at 60 km the trough has taken the position of the ridge in the stratosphere (20 to 35 kilometers).

At 60 km (figure 10) data are very sparse and are mainly based on grenade soundings at Churchill and Wallops Island. There is evidence that the zonally oriented trough over North America still exists, as indicated by strong winds from the

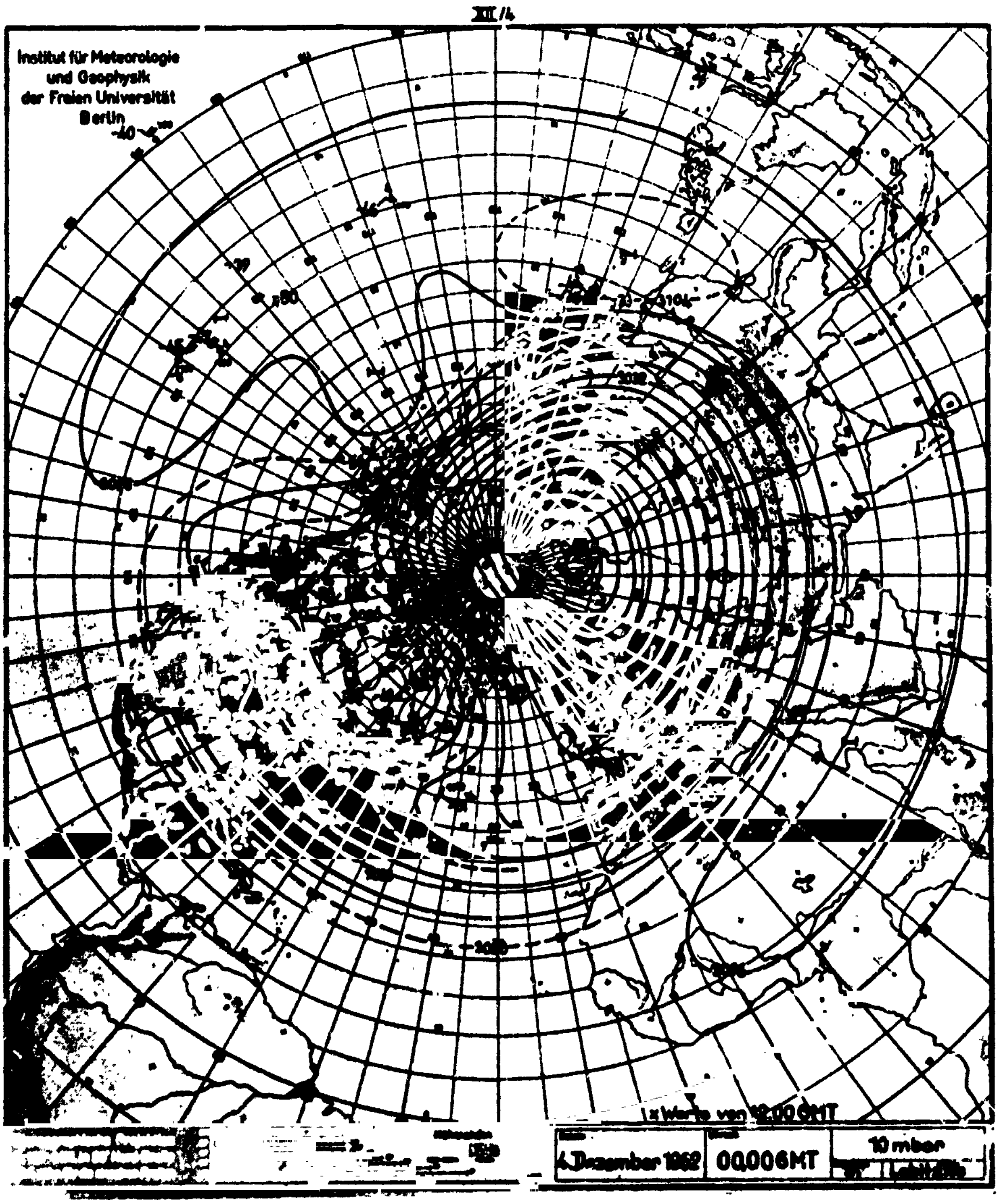


FIGURE 5

west south-west over the United States and very light northwesterly wind inside the trough over Churchill on 4 December, 1962. In general, it is interesting to note the alternation between low and high pressure systems on a vertical scale between the 30 and 60 km levels as shown in figures 5–10. This seems to confirm the theoretical expectation of such alternations previously expressed by Paetzold (15).

Differences in the flow and pressure patterns between 4 December and 6 December were found to be insignificant at 40, 50, and 60 km. This is

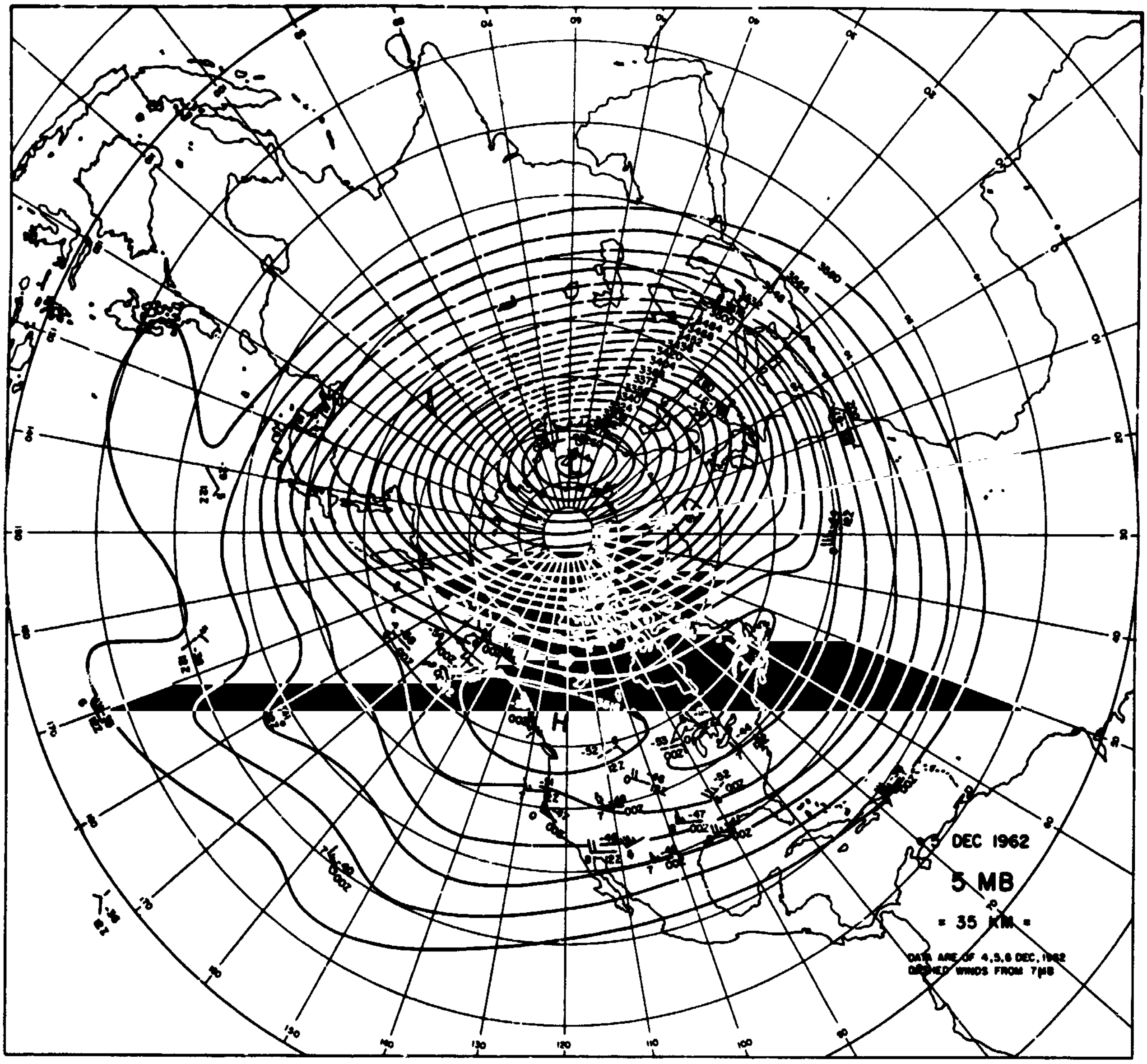
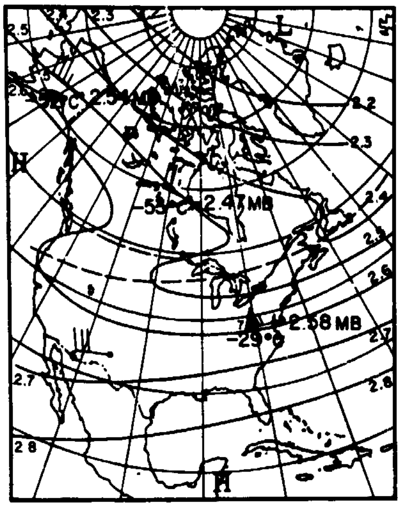


FIGURE 6

not surprising because the patterns in the stratosphere also remained nearly unchanged. At 68 km, however, a significant change seems to have taken place between 4 December and 6 December over Churchill and 1 December and 6 December over Wallops Island. There is a 90 degree rotation of the wind vectors at both stations, but at Churchill this rotation is clockwise, while at Wallops Island it is counter clockwise. This may be interpreted as a southwestward motion of the low pressure system (figures 10A, 10B).

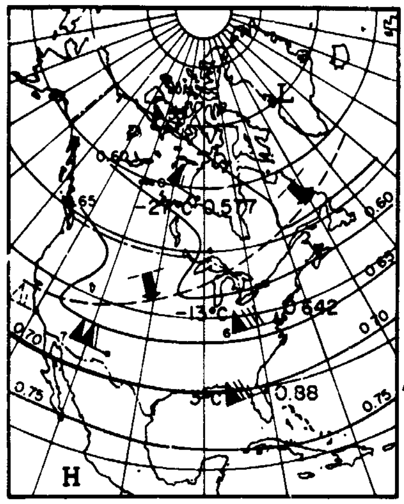
Of course, the sparsity of data permits only a very crude analysis even in this case, which could be considered well documented by rocket sounding standards. Nevertheless, this case shows that significant nonuniformities exist in the slopes of the constant pressure surfaces which are generally inclined downward toward the winter pole. If in the past such uniformity was assumed, it was only because the available data were not sufficient to observe any detail. It is to be expected that systematic rocket observations of the mesosphere extended over the hemisphere and spaced over distances in the order of 1000 km will reveal up to about 70 km circulation systems of similar variability and variety as observed at lower altitudes.



40 km
DEC 4, 1962

LEGEND
WINDS IN m/sec
DATA AT WALLOPS ISLAND DEC. 1, 1962

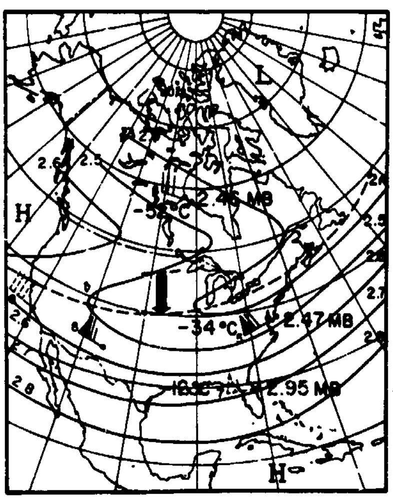
FIGURE 7A.



50 km
DEC 6, 1962

LEGEND
WINDS IN m/sec
Δ -- DATA FOR DEC 7 '62

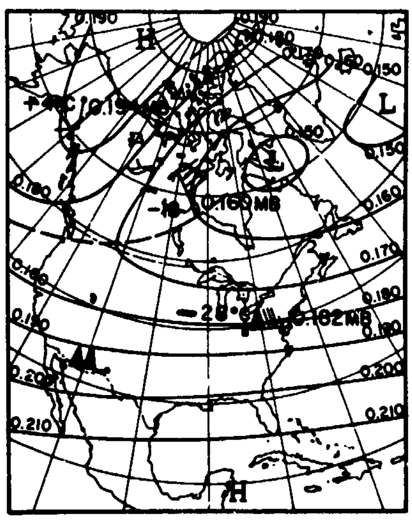
FIGURE 8B.



40 km
DEC 6, 1962

LEGEND
WINDS IN m/sec
Δ -- DATA FOR DEC. 7 '62

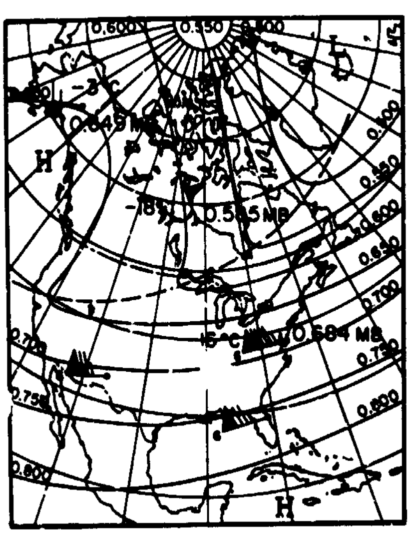
FIGURE 7B.



60 km
DEC 4, 1962

LEGEND
WINDS IN m/sec
DATA AT WALLOPS ISLAND DEC. 1, 1962

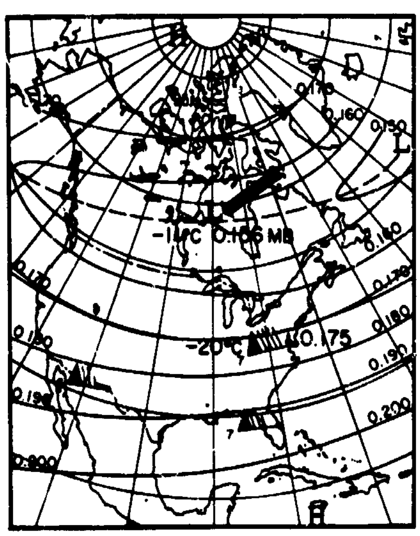
FIGURE 9A.



50 km
DEC 4, 1962

LEGEND
WINDS IN m/sec
DATA AT WALLOPS ISLAND DEC. 1, 1962

FIGURE 8A.



60 km
DEC 6, 1962

LEGEND
WINDS IN m/sec

FIGURE 9B.

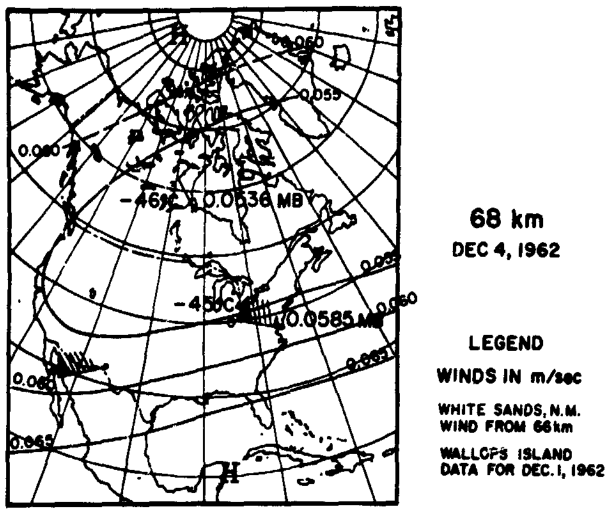


FIGURE 10A.

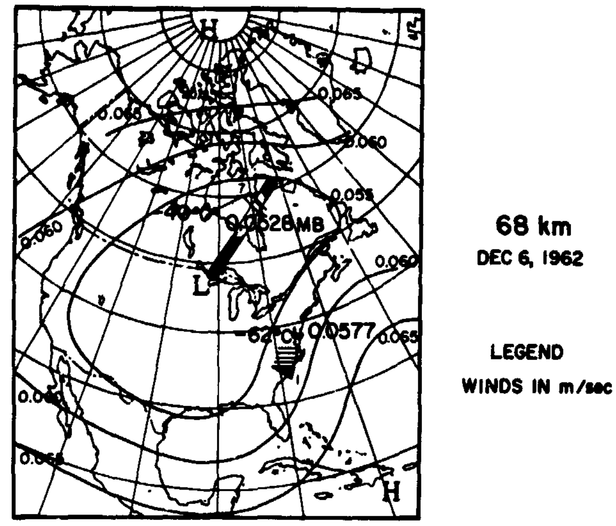


FIGURE 10B.

REFERENCES

1. NORDBERG, W., and STROUD, W., "Seasonal, Latitudinal and Diurnal Variations in the Upper Atmosphere," NASA, Technical Note TN D-703, Washington, D. C., April 1961.
2. NORDBERG, W., and SMITH, W., "Rocket Measurements of the Structure of the Upper Stratosphere and Mesosphere," Institut fur Meteorologie und Geophysik der Freien Universitaet Berlin, Meteorologische Abhandlungen, Band XXXVI (1963) p. 391–400.
3. NORDBERG, W., "Rocket Soundings in the Mesosphere," Astronautics and Space Engineering, Vol. 2, May 1964, American Inst. for Aeronautics and Astronautics, Publisher.
4. MIERS, B. T., "Zonal Wind Reversal between 30 and 80 km over Southwestern United States," Journal Atm. Sciences, Vol. 20, pp. 87–93, (1963).
5. MANRING, et al., "An Experimentally Determined Model for the Periodic Character of Winds from 85 to 35 km," GCA Technical Rep. No. 63-27-N Contract No. NAS W-712, Geophysics Corporation of America, November 1963.
6. SCHERHAG, R., "Eine erste synoptische Hoehenwetterkarte der 0.5 mbar-Flaeche," Berliner Wetterkarte, Beilage 33, Mai 1961 (1961).
7. WARNECKE, G., "Eine synoptische Hoehenwetterkarte fuer das 0.5 mbar-Niveau vom Sommer 1960," Berliner Wetterkarte, Beilage 37, Mai 1961 (1961).
8. KEEGAN, T. J., "Synoptic Patterns at 100,000 to 200,000 Feet," Air Force Surveys in Geophysics No. 140 AFCRL-62-273 (II), 195–210 (1962).
9. FINGER, F. G., and TEWELES, S., "Synoptic Charts Based on Rocketsonde Data," Institut fur Meteorologie und Geophysik der Freien Universitaet Berlin, Meteorologische Abhandlungeh, Band XXXVI (1963), pp. 379–390.
10. SMITH, W., KATCHEN, L., SACHER, P., SWARTS, P., THEON, J., "Temperature, Pressure, Density and Wind Measurements with the Rocket Grenade Experiment, 1960–1963, NASA, Goddard Space Flight Center, May 1964.
11. "Data Report of the Meteorological Rocket Network," December 1962. Prepared by U. S. Army Signal Missile Support Agency. White Sands Missile Range, New Mexico.
12. SCHERHAG, R. et Coll., "Taegliche Hoehenkarten der loo mb Flaeche sowie monatliche Mittelkarten fuer das Jahr 1962," Institut fuer Meteorologie und Geophysik der Freien Universitaet Berlin, Meteorologische Abhandlungen, Band XXIII, Teil IV.
13. SCHERHAG, R. et Coll., "Preliminary Daily Northern Hemisphere 30 mb Synoptic Weather Maps of the Year 1962," Institut fuer Meteorologie und Geophysik der Freien Universitaet Berlin, Meteorologische Abhandlungen, Band XXV, Part IV.
14. SCHERHAG, R. et Coll., "Preliminary Daily Northern Hemisphere 10 mb Synoptic Weather Maps of the Year 1962," Institut fuer Meteorologie und Geophysik der Freien Universitat Berlin, Meteorologische Abhandlungen, Band XXVI, Part IV.
15. PAETSOLD, H. K., "On the Problem of Solar Activity Effects on the Lower Terrestrial Atmosphere," Institut fur Meteorologischie und Geophysik der Freien Universitat Berlin, Meteorologische Abhandlungen, Band XXXVI (1963).